RESEARCH PAPER

Land-use, biomass and carbon estimation in dry tropical forest of Chhattisgarh region in India using satellite remote sensing and GIS

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Abstract : A study was conducted to characterize the land use, biomass and carbon status of dry tropical forest in Raipur district of Chhattisgarh, India using satellite remote sensing data and GIS techniques in the year of 2001−2002. The main forest types observed in the area are Teak forest, mixed forest, degraded forest and Sal mixed forest. The aspect and slope of the sites influenced the forest vegetation types, biomass and carbon storage in the different forests. The standing volume, above ground biomass and carbon storage varied from 35.59 to 64.31 $m^3 \cdot ha^{-1}$, 45.94 to 78.31 $Mg \cdot ha^{-1}$, and 22.97 to 33.27 $Mg \cdot ha^{-1}$, respectively among different forest types. The highest volumes, above ground biomass and carbon storage per hectare were found in the mixed forest and lowest in the degraded forest. The total standing carbon present in the entire study area was 78170.72 Mg in mixed forest, 81656.91 Mg in Teak forest, 7833.23 Mg in degraded forest and 7470.45 Mg in Sal mixed forest, respectively. The study shows that dry tropical forests of the studied area in Chhattisgarh are in growing stage and have strong potential for carbon sequestration.

Keywords: biomass; carbon storage; aspect; slope

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Introduction

Tropical forest ecosystem is one of the richest terrestrial ecosystems, which stores approximately half of the world living terrestrial carbon and a very significant proportion is fixed in the form of above ground biomass, thus they play an important role in global carbon cycle and regulating the biospheric climate. Besides, these forest ecosystems also support variety of life forms and maintain huge global biodiversity (Shi et al. 2002). However, the increasing rates of deforestation, biomass burning, land use transformations coupled with rapid industrialization from the last few decades not only depleting the diversity but also releasing enormous quantities of CO_2 into the atmosphere. The net Carbon release from tropical forests was estimated about (1.6±0.4) Gt C annually, accounting for 21% of the global carbon annually which is almost equivalent to 20%−65% of the emissions from fossil fuels (Houghton 1991). Due to alarming rates of anthropogenic interferences, the CO_2 concentration in the atmosphere was increased by 15%−25% over the past 100 years (Haripriya 2000).

Presently, there is neither any quantitative nor any qualitative information available on land use and vegetation status in dry tropical forests of Chhattisgarh, India. No reports are available on plant structure, biomass, carbon storage, and also no attempts were initiated to understand the physiographic influences on vegetation and land use status in dry tropical ecosystems of this region. In view of this, the present study was carried out to quantify the existing land use, volume, biomass, and carbon storage status.

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Materials and methods

Study area

The study was carried out in Balamdi watershed, which is a part of Barnawapara Sanctuary, Raipur district in Chhattisgarh, India during 2001−2002 (Fig. 1). The study area is spread in between 21º20' to 21º26' North latitudes and 82º21' to 82º26' East longitudes. A dry tropical ecosystem of Raipur forest division was selected for characterizing land use, vegetation, volume, biomass, and carbon storage in different vegetation types. The watershed comprises an area of 7 200 ha, of which more than 70% area is predominantly covered by different forests.
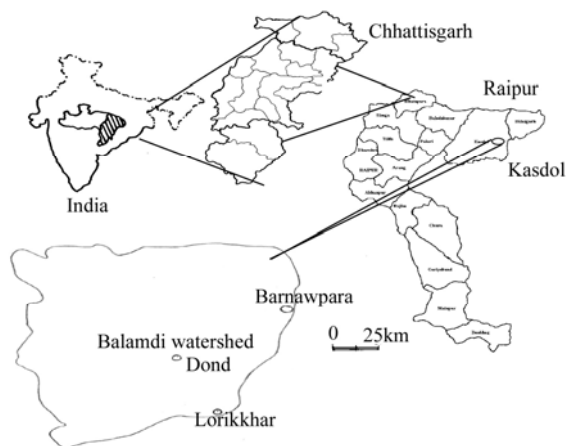

Fig. 1 Location map of study area

The climate of study area is dry humid tropical and consists of three major seasons viz. rainy, winter and summer. The average annual rainfall in the study area ranges from 1200–1350 mm with the highest amount of rainfall in July. The mean monthly maximum temperature of the study area varies from 27.3 ºC in January to 41.8ºC in May and mean monthly minimum temperature from 12.7ºC in December to 27.3ºC in May.

Vegetation analysis

Land-use and vegetation status of study area is analyzed using satellite remote sensing and GIS techniques with field measurements. Remote sensing satellite data were digitally analyzed for delineation of different land use and vegetation types to serve as primary stratification units (PSUs). The vegetation analysis was first performed in these strata. Later, the ancillary data collected from 64 k/7 number Survey of India (SOI) topomap (1:50 000) were used for deriving different physiographic maps in GIS environment.

The cloud free remote sensing digital data of IRS 1D LISS III of path 103 and row 57 during December 2001 were procured from National Remote Sensing Agency (NRSA), Hyderabad, India (Fig. 2). The digital analysis of data was performed using ERDAS Imagine (Version 8.4) software in Silicon Graphics (SGI) systems and the ancillary data collected from SOI topomaps was analyzed using ARC/INFO (version 8.1) software in

GIS environment. Both remote sensing and GIS analysis was carried out at Regional Remote Sensing Service Centre, Indian Space Research Organization (ISRO), Dehradun, India.

The digital classification of land use and vegetation was done by supervised classification using maximum likelihood algorithm. The process involves identification of spectrally homogenous areas, which can serve as a signature for a particular land use class and called as 'training areas'. The NDVI map was generated to see the variation in biomass distribution in different physiographic regions of study area. The colour coded map was generated on the basis of NDVI and ranges for different cover types. The contour and drainage maps of study area were prepared from Survey of India toposheet. The contour information was used for preparation of elevation, slope and aspects maps. The slope and aspect maps were overlaid on classified image to quantify the physiographic effects on vegetation, volume, biomass, and carbon storage in different forest types. The spatial extent of all these strata was calculated to extrapolate results of field sampling plots to entire area.

Phytosociological analysis for the structural characterization of tree communities in each forest type was performed in two stages. In the first stage, the aspect wise analysis was done to quantify the effect of physiographic variation in relation to structural variation in tree communities of a given forest type. In second stage, the data collected from different aspects of a given forest type were combined and pooled analysis was performed to determine the overall tree structure of the particular forest type in study area.

Sampling

The stratified random sampling approach was adopted for laying sample plots in different forest types to estimate the structure, standing volume, biomass and carbon storage. The analysis of woody perennial in each forest strata has been carried by randomly laying sample plots of 20 m × 20 m. In each sample plot, the trees were enumerated for their diameters at breast height (DBH) and heights and put in the definite diameter and height classes. The DBH of individual tree was measured at 1.37 m above ground level using tree caliper while the height of trees was measured by Abney's level.

Estimation of tree volume, above ground biomass and carbon

The DBH and height of trees measured in all major forest types in each sampling quadrat were used for computation of standing volume existing in different forest types. The species specific volume equations compiled by Forest Survey of India (FSI 1996) were used to compute the volume of the trees (Table 1). In order to estimate the tree biomass, the volume of individual tree in each sampling quadrat was multiplied by its mean density and thus stem biomass was derived (Table 2). Later, the stem biomass was multiplied by the biomass expansion factor of respective species to derive above ground biomass. The carbon storage for each tree was computed by multiplying biomass values with 0.5 as per the method from references (Haripriya 2000; Smith et

al. 2002; Heath 2007; Smith et al. 2007). The above ground biomass and carbon contents of individual trees in a quadrat were summed to obtain total above ground tree biomass and carbon present in that sampling quadrat. The mean above ground biomass and carbon were calculated by averaging the biomass and carbon values in all sampling quadrates laid in a stratum. Later the mean values were extrapolated to obtain above ground bio-

mass and carbon storage per ha basis. To quantify effects of physiographic features, the biomass and carbon content were also measured in various forest types falling in different slopes and aspect classes. Later, the total standing mean values above ground biomass and carbon storage for each strata (forest type) were calculated by multiplying the mean values of biomass and carbon with their respective areas.
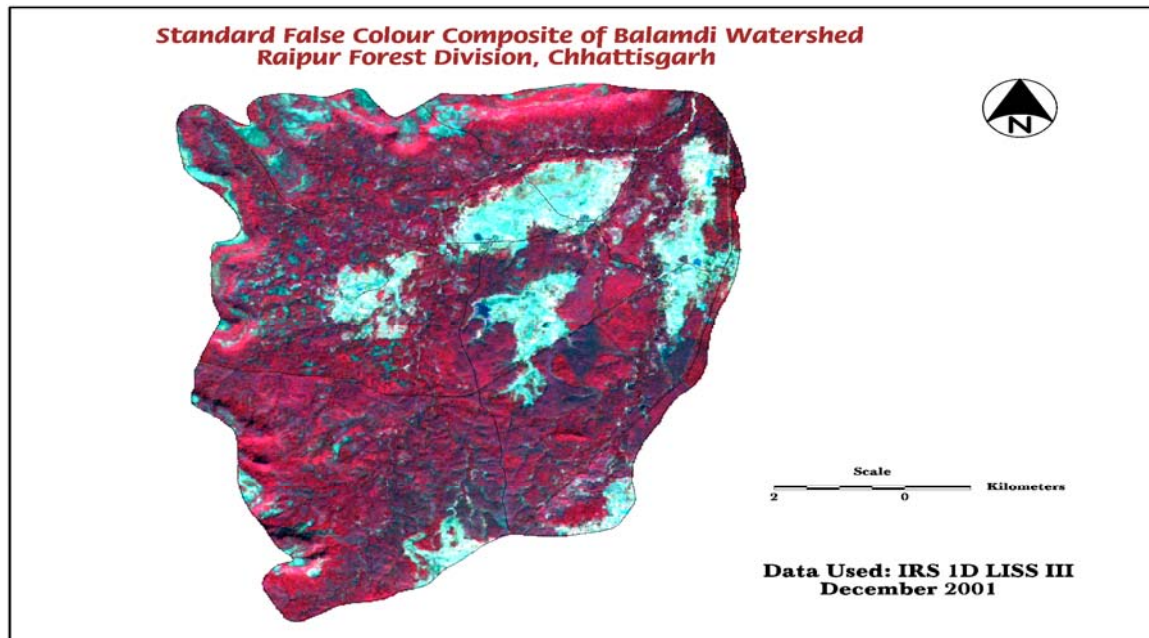

Fig. 2 Standard false colour composite (RS data) of Balamdi watershed

Table 1. Volume equations used for computation of above ground volume of different tree species

S.N.	Name of species	Volume equation	n	R^2
1	*Anogeissus latifolia*	$\sqrt{v} = 0.28802 + 5.12791\,D - 1.87116\,\sqrt{D}$ (L)	251	0.92310
2	*Cleistanthus collinus*	$V = -0.00287 + 0.38065\,D^2H$ (G)	100	0.9305
3	*Dalbergia latifolia*	$V = 0.044221 + 2.3284650\,D^2 + 0.309150\,D^2H$ (G)	-	-
4	*Dalbergia sissoo*	$\sqrt{v} = -0.3238 + 3.0077\,D$ (G)	1146	0.9358
5	*Bombax ceiba*	$V/D^2 = 0.0417/D^2 - 0.47789/D + 3.5014 + 9.76048\,D$ (L)	34	0.70256
6	*Cassia fistula*	$V = 0.066 + 0.287\,D^2H$ (G)	-	-
7	*Chloroxylon swietenia*	$V = -0.009 + 0.236\,D^2H$ (G)	-	-
8	*Acacia catechu*	$V = 0.043849 - 0.552735\,D + 2.952386\,D^2 + 0.334508\,D^2H$	46	-
9	*Diospyros melanoxylon*	$V/D^2 = -0.04233/D^2 + 0.49232/D - 0.00858 + 13.27481\,D$ (L)	227	0.76395
10	*Grewia tiliaefolia*	$V = -0.035 + 0.307\,D^2H$ (G)	52	0.909
11	*Pterocarpus marsupium*	$V = 0.06801 + 0.14032\,D + 1.43895\,D^2 + 18.34982\,D^3$ (L)	65	0.54428
12	*Shorea robusta*	$V = 0.48104 - 6.28923\,D + 24.48398\,D^2 - 9.205153\,D^3$ (L)	626	0.98394
13	*Syzygium cumini*	$V = -0.002043 + 0.361337\,D^2H$ (G)	-	-
14	*Tectona grandis*	$V/D^2 = 0.12591/D^2 - 2.45212/D + 16.52336 - 7.57135\,D$ (L)	124	0.85328
15	*Terminalia belerica*	$\sqrt{v}\ -0.15683 + 3.01055\,D$ (L)	46	0.96798
16	*Terminalia tomentosa*	$V = 0.00376 - 0.77604\,D + 8.35533\,D^2$ (G)	458	0.97007
17	*Madhuca indica*	$V = -0.014 + 0.275\,D^2H$ (G)	-	-
18	*Zizyphus maurisiana*	$V = -0.002557 + 0.260114\,D^2H$ (G)	-	-
19	*Miscellaneous species*	$V/D^2\ 0.03646 - 0.91545/D + 7.71869 + 1.15753D$ (R)	2684	0.73337

Notes: n represents Total number of sample trees were used for deriving regression equation; R^2 represents Co-efficient of determination; L represents Local volume equation; G represents General volume equation; R represents Regional volume equation; $\sqrt{v}$ or V represents Volume of tree; $\sqrt{D}$ or D represents Diameter of tree at breast height; H represents Height of tree; Source: FSI (1996), Dehradun, India.

The data on volume, biomass and carbon storage were analyzed using one way analysis of variance with unequal number of replications to test the variability among different forest types in MSTAT C statistical package under PC environment.

Table 2. Mean wood density and biomass expansion factors used in the present study

S.No.	Names of species	Wood density *Mg·m^{-3}	**Biomass expansion factor
1	Acacia catechu	1.010	1.59
2	Anogeissus latifolia	0.850	1.59
3	Bombax ceiba	0.385	1.51
4	Cassia fistula	0.865	1.51
5	Chloroxylon swietenia	0.960	1.51
6	Cleistanthus collinus	0.850	1.59
7	Dalbergia latifolia	0.815	1.59
8	Dalbergia sissoo	0.780	1.59
9	Diospyros melonoxylon	0.835	1.59
10	Grewia tiliaefolia	0.785	1.51
11	Madhuca indica	0.915	1.51
12	Pterocarpus marsupium	0.800	1.51
13	Shorea robusta	0.855	1.59
14	Syzygium cumini	0.785	-
15	Terminalia bellerica	0.815	-
16	Terminalia tomentosa	0.880	1.51
17	Tectona grandis	0.650	1.59
18	Zizyphus mauritiana	0.705	-
19	Miscellaneous species	0.641	1.53

Notes: Mg = Mega gram = 10^6 gram; **Haripriya (2000); *Ramesh Rao et al. (1983); *Indian Forest Utilization, Volume II, F.R.I., Dehradun, India.

Results and discussion

Land-use, vegetation and phytosociology

The land use and vegetation classification of study area were done using Maximum likelihood algorithm and the results on spatial extent of different categories of land cover along with their classification accuracies were shown in Table 3 and Fig. 3. Nine land cover and vegetation classes viz. Teak forest, mixed forest, open grass lands, degraded forest, dense grass land/scrub, Sal (*Shorea robusta*) mixed forest, agriculture, habitation and water bodies were delineated. The presence of tree species in the different forest types and their Importance Value Index (IVI) are shown in Table 4. Results showed that the trees of *Madhuca indica* (20.78), *Tectona grandis* (112.49), *Buchanania lanzan* (44.43) and *Shorea robusta* (78.62) are dominating in Mixed forest, Teak Mixed forest, Degraded forest and Sal Mixed forest, respectively. The classified image (Fig. 4) showed the spatial distribution of different land use and vegetation categories. The land use and vegetation were digitally classified using satellite data through maximum likelihood algorithm. The earlier studies also demonstrated the use of remote sensing satellite data in a number of classification schemes for characterizing land use

types (Townshed et al. 1987; Tuomisto et al. 1994). The land use and vegetation mapping through satellite remote sensing were done in different environments using various classification algorithms by several researchers (Saxena et al. 1992; Sudhakar et al. 1994; Krishana et al. 2001).

Table 3. Spatial extent of vegetation types and other land use patterns

S.No.	Vegetation and Land use categories	Area (ha)	Accuracy (%)
1	Teak Forest	2461.77	87
2	Mixed Forest	1998.74	84
3	Open Grassland	1674.25	80
4	Degraded Forest	341.02	77
5	Dense Grassland/Scrub	322.21	74
6	Sal Mixed Forest	224.54	64
7	Agriculture area	99.10	65
8	Habitation	43.49	69
9	Water	35.14	90
	Total	7200.26	-
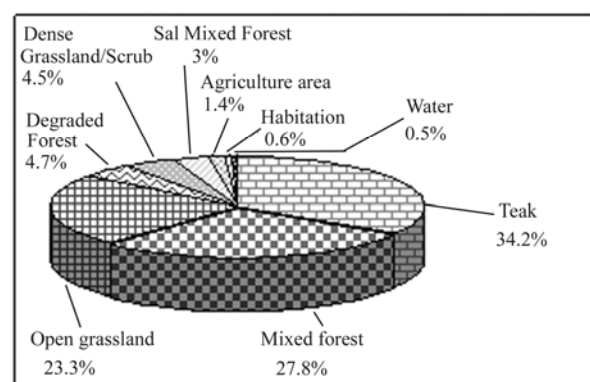
Fig. 3 Distribution of land use and vegetation types

All these studies concluded that maximum likelihood classification was a most useful classification technique for different environments. The maximum likelihood classifier is better because it is based on the decision rule that pixels of unknown class membership would be allocated to those land cover classes which fall in highest likelihood of membership (Foddy et al. 1996). The maximum likelihood classification helped in achieving better classification accuracies ranging from 65% to 100% for different land use classes. The overall accuracy of 80% was achieved by this technique in this study. Saha et al. (1990) also reported overall accuracy of 96% in wasteland classification of Aligarh district, U.P. India through digitally classifying Landsat TM data using maximum likelihood algorithm. The higher classification accuracies were also obtained by several other researchers using this classification technique (Sugumaron et al. 1994; Sehghal et al. 1997; Mahajan et al. 2001).

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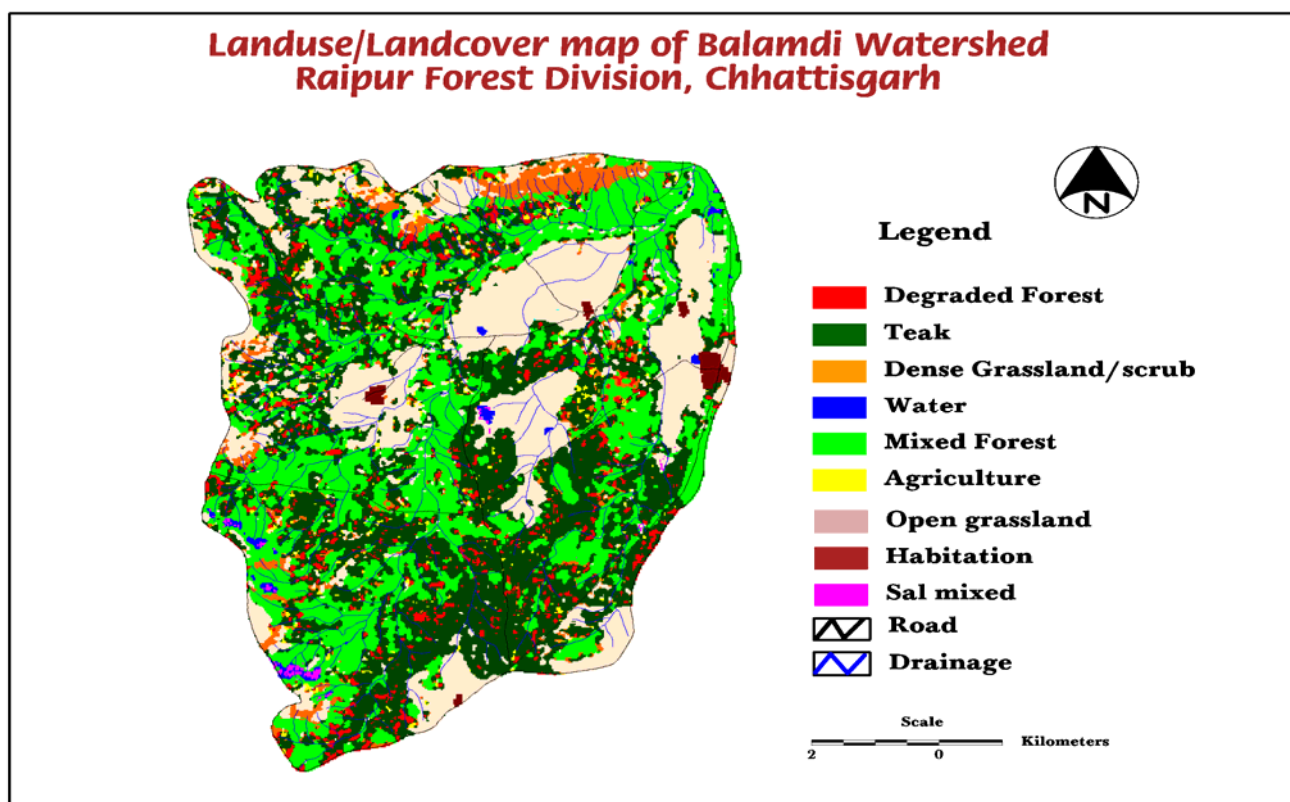
Fig. 4 Landuse and landcover map of Balmdi watershed

The study area is predominantly covered by forest vegetation, grass lands and scrubs, which accounted for 97.54% of total geographical area and remaining 2.46% area is covered by agriculture, water bodies and habitat (Fig. 3). Among the different land use and vegetation types, Teak forest occupied the largest area, which was 34.19 % of the total geographical area. The other prominent vegetation classes followed by Teak were mixed forest and open grass lands, which covered in 27.78% and 23.25 % of the total area. The water bodies occurred only in 0.49% of the total area. Agriculture is only practiced in 1.37% area of the watershed. Teak forest is covered in largest area comprising of 2461.77 ha followed by mixed forests in 1998.75 ha, open grass lands in 1674.25 ha and degraded forests in 341.02 ha (Table 3). Sal mixed forest is found in patches and covered in an area of 224.54 ha. The classification accuracy for different land use categories ranged from 64% to 90%. The maximum accuracy was attained by water bodies (90%) followed by Teak forest (87%), mixed forest (84%), open grass land (80%), degraded forest (77%), dense grass land/scrub (74%), habitation (69%), agriculture area (65%) and Sal mxed forest (64%) as presented in Table 3. Sal mixed forest types attained poor accuracy as compared to other vegetation and land use types. The present study also showed that higher classification accuracies were achieved for certain vegetation classes like Teak forest, degraded forest, dense grass land and water bodies. This may be ascribed to distinct spectral behaviour of these types, which are easily separable and used in achieving better accuracies than the other classes. However, the Sal mixed forest and mixed forest, open grass land and agriculture classes showed lower accuracies because the pixels of these classes were intermixed with each other. They were also not spectrally as homogenous as other classes like Teak and degraded forests. Ravan et al. (1996) evaluated the accuracy of vegetation classification of dry deciduous forests of Madhav National Park, M.P., India through digital and visual interpretation of Landsat TM data. The temporal data had a higher classification accuracy (67.07%), compared to single date satellite data. Kachhawaha (1993) achieved better classification accuracy by using multitemporal data in vegetation and land use analysis of Rajaji national park, Dehradun, India. He further demonstrated that Sal forest and Teak plantations could be identified and delineated by only using IRS-1A LISS II imagery in dry season (April). This was possible because most of these species were leafless at the first week of May. The Sal trees never become completely leafless and because of these phenological characteristics, Sal forest was more easily distinguished from other types of forests on the satellite imagery of May month. Therefore, the remote sensing data can also describe qualitative characters and structural variations in plant communities (William et al. 1986; Thomas et al. 1993). The effectiveness of multitemporal data for improving the level of classification and accuracy was also reported by Sehgal et al. 1997; Jayakumar et al. 2000.

Table 4. Importance value index (IVI) of tree species in different forest types

| Name of the species	IVI (RD+RF + RBA)[*]			
	Mixed forest	Teak mixed forest	Degraded forest	Sal mixed forest
Acacia catechu	7.77	-	-	-
Anogeissus latifolia	13.03	11.38	-	23.19
Boswellia serrata	17.29	17.22	29.35	29.49
Bombax ceiba	8.88	-	-	-
Bridelia retusa	8.66	-	-	-
Buchanania lanzan	12.57	8.50	44.93	21.69
Cleistanthus collinus	18.95	26.35	34.83	-
Cassia fistula	8.21	-	-	-
Chloroxylon swietenia	9.32	-	-	-
Dalbergia sissoo	10.41	11.10	13.62	-
Dalbergia latifolia	11.77	-	-	-
Diospyros melanoxylon	17.20	16.21	32.75	31.61
Emblica officinalis	10.46	6.04	-	-
Ficus hispida	6.31	-	-	-
Grewia tiliaefolia	5.98	-	-	-
Madhuca indica	20.78	26.39	40.31	41.61
Nyctanthes arbortristis	6.83	-	-	-
Ougeinia oojeinensis	8.98	7.79	22.81	15.88
Pterocarpus marsupium	18.53	-	-	-
Schleichera oleosa	17.31	28.02	22.14	-
Shorea robusta	11.27	11.09	-	78.62
Tectona grandis	15.51	112.49	26.00	33.29
Syzygium cumini	7.31	-	-	-
Terminalia tomentosa	16.19	17.43	33.62	24.83
Terminalia bellerica	6.23	-	-	-
Zizyphus mauritiana	4.14	-	-	-
Total	300.00	300.00	300.00	300.00

Notes: * RD is Relative Density, RF is Relative Frequency, RBA is Relative Basal Area.

Standing volume, biomass and carbon storage in different forest types

Four different forest types were recorded in the area viz. Mixed forest, Teak mixed forest, Degraded forest, Sal mixed forest. The standing volume, biomass and carbon storage in different forests were estimated in the present study on the basis of aspects (direction of slope with respect to the sun) and slopes (angle of geographical terrain). Data in Table 5 showed that the mean volume ranged from 35.59 to 64.31 $m^3 \cdot ha^{-1}$, biomass from 45.94 to 78.31 $Mg \cdot ha^{-1}$ and Carbon from 22.97 to 39.11 $Mg \cdot ha^{-1}$ in different forest types. Analysis of variance indicated that mean volume, biomass and carbon storage had significant variation among different forest types. Results on paired comparison showed that all the four types of forests significantly differed from each other for volume, while Teak and Sal mixed forests did not show any differences among themselves for the biomass and carbon storage.

The significantly higher volume, biomass and above ground carbon storage were recorded in mixed forests and lowest in degraded forests. The volumes of mixed forest, Teak forest and Sal mixed forest were 1.80, 1.49 and 1.23 times higher than the

volume of degraded forests respectively. Similarly, the above-ground biomass and carbon storage were 1.7, 1.44 and 1.45 times higher those in mixed, Teak and Sal mixed forests as compared to that in degraded forests (Table 5). The estimated standing volume in the present study is comparable to volume in other tropical forests (Swamy 1998; Ravindranath et al. 1994; Haripriya 2000). Haripriya (2000) in their study reported that the average standing volume for deciduous forests was 37.9 $m^3 \cdot ha^{-1}$, Teak 49.5 $m^3 \cdot ha^{-1}$, Sal 44.1 $m^3 \cdot ha^{-1}$ and Salai (*Boswellia serrata*) 54.2 $m^3 \cdot ha^{-1}$. However, the volumes in the present study were comparatively lower than volumes studied by Swamy (1998), which ranged from 163.0 to 380 $m^3 \cdot ha^{-1}$ in tropical semi ever-green forests of Western Ghats, India. The lower volume in the present study is attributed to the more number of trees present in lower diameter classes (Fig. 5). In tropical semi-evergreen forests, the average girth of trees was almost 4 to 5 times higher than that of the forest of present study. The lower tree density was also a possible cause for the lower standing volume in the present study. The total standing volume, biomass and carbon storage of each forest type in the watershed were obtained by multiplying the mean values per hectare of these parameters with respective areas of particular forest type in the watershed. The standing volume was 128 538.96 m^3 in the mixed forest, 130 818.45 m^3 in Teak forest, 12 136.90 m^3 and 9 832.60 m^3 in degraded forest and Sal mixed forest, respectively (Table 5).
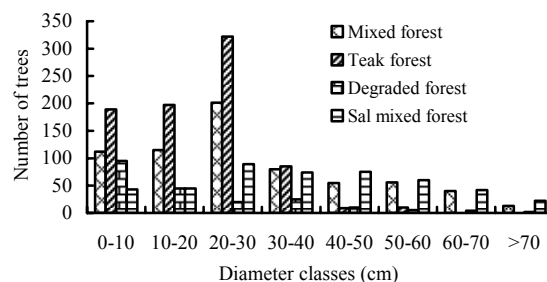
Fig. 5 Distribution of per diameter class in per hectare under different forests

The distributions of volume, biomass and carbon storage in different aspects in different forest types were presented in Table 6. In the northern aspect, the total standing volume ranged from 41.37 to 69.47 $m^3 \cdot ha^{-1}$ in different forest types. Similarly, in the southern aspect, it ranged from 39.22 to 58.54 $m^3 \cdot ha^{-1}$, in the eastern aspect from 31.81 to 67.22 $m^3 \cdot ha^{-1}$ and in the western aspect from 26.29 to 72.44 $m^3 \cdot ha^{-1}$. The average volume of all four forest types showed that there were the higher volumes for 52 $m^3 \cdot ha^{-1}$ and 49.58 $m^3 \cdot ha^{-1}$ in northern and southern aspects, while there were the higher biomass values for 66.53 $Mg \cdot ha^{-1}$ and 64.96 $Mg \cdot ha^{-1}$ in southern and northern aspects, respectively. In the northern aspect, the above ground biomass of different forest types ranged from 51.44 to 79.32 $Mg \cdot ha^{-1}$, in the southern aspect from 50.23 to 72.62 $Mg \cdot ha^{-1}$, in the eastern aspect from 48.44 to 75.62 $Mg \cdot ha^{-1}$ and in the western aspect from 31.85 to 87.46 $Mg \cdot ha^{-1}$. The carbon storage also showed similar trend like biomass distribution in different aspects. Mean Carbon storage was the highest in southern aspect and lowest in western aspect (Table 6). In the northern aspect, the above ground carbon stor-

age in different forest types ranged from 25.72 to 39.66 Mg·ha⁻¹C, in the southern aspect from 25.13 to 36.31 Mg·ha⁻¹ C, in the eastern aspect from 24.22 to 37.81 Mg·ha⁻¹C and in the western aspect from 15.92 to 43.73 Mg·ha⁻¹C (Table 6). Among all the aspects, western aspect showed the highest values for standing volume, biomass and carbon storage in mixed forest, whereas lowest values were observed in degraded forest in the same aspect (Table 6).

Table 5. Distribution of mean standing volume, biomass and carbon storage in different forest types

Forest types	Area of forest type (ha)	Mean standing volume (m³·ha⁻¹)	Total standing volume (m³)	Mean above ground bio-mass (Mg·ha⁻¹)	Total above ground biomass (Mg)	Mean carbon in above ground bio-mass (Mg·ha⁻¹)	Total above ground "C" storage (Mg)
Mixed Forest	1998.74	64.31	128538.96	78.31	156521.13	39.11	78170.72
Teak Mixed Forest	2461.77	53.14	130818.45	66.34	163313.82	33.17	81656.91
Degraded Forest	341.02	35.59	12136.90	45.94	15666.45	22.97	7833.23
Sal Mixed Forest	224.54	43.79	9832.60	66.54	14940.89	33.27	7470.45
L.S.D. for Type 1* Vs 2*		4.19		4.98		2.74	
L.S.D. for Type 1* Vs 3*		5.85		6.95		3.82	
L.S.D. for Type 1* Vs 4*		7.04		8.36		4.60	
L.S.D. for Type 2* Vs 3*		5.62		6.68		3.67	
L.S.D. for Type 2* Vs 4*		6.85		NS		NS	
L.S.D. for Type 3* Vs 4*		7.97		9.47		5.21	

Notes: L.S.D. represents Least Significant Difference;1* represents Mixed Forest; 2* represents Teak Mixed Forest ; 3* represents Degraded Forest; 4* represents Sal Mixed Forest; NS is Non Significant.

Table 6. Distribution of mean standing volume, biomass and carbon storage in different forest types (Aspect wise)

Forest type	Volume (m³·ha⁻¹)			
	North	South	East	West
Mixed Forest	69.47	48.11	67.22	72.44
Teak Mixed Forest	49.74	58.54	57.51	46.65
Degraded Forest	41.37	39.22	35.48	26.29
Sal Mixed Forest	47.42	52.46	31.81	43.47
Mean	52.00	49.58	47.98	47.21
Forest type	Biomass (Mg·ha⁻¹)			
	North	South	East	West
Mixed Forest	79.32	70.84	75.62	87.46
Teak Mixed Forest	60.64	72.62	68.44	63.84
Degraded Forest	51.44	50.23	48.44	31.85
Sal Mixed Forest	68.44	72.44	65.43	59.85
Mean	64.96	66.53	64.48	60.75
Forest type	Carbon (Mg·ha⁻¹)			
	North	South	East	West
Mixed Forest	39.66	35.42	37.81	43.73
Teak Mixed Forest	30.32	36.31	34.22	31.92
Degraded Forest	25.72	25.13	24.22	15.92
Sal Mixed Forest	34.22	36.22	32.71	29.92
Mean	32.48	33.26	32.24	30.37

ranged from 37.32 to 51.61 Mg·ha⁻¹C, 21.06 Mg·ha⁻¹C to 35.77 Mg·ha⁻¹C and 10.05 Mg·ha⁻¹C to 16.37 Mg·ha⁻¹C (Table 7).

Table 7. Distribution of mean standing volume, biomass and carbon storage in different forest types (Slope wise)

Forest type	Volume (m³·ha⁻¹)		
	Gentle (0-20%)	Moderate (21%-40%)	Steep/High (>40%)
Mixed forest	93.02	60.2	40.51
Teak mixed forest	71.30	50.21	39.84
Degraded forest	51.23	32.1	26.21
Sal mixed forest	68.21	41.32	22.65
Mean	70.94	45.96	32.30
Forest type	Biomass (Mg·ha⁻¹)		
Mixed forest	103.23	71.54	21.65
Teak mixed forest	97.3	64.54	32.74
Degraded forest	74.65	42.13	20.10
Sal mixed forest	96.31	62.31	29.31
Mean	92.87	60.13	25.95
Forest type	Carbon (Mg·ha⁻¹)		
Mixed forest	51.61	35.77	10.82
Teak mixed forest	48.65	32.27	16.37
Degraded forest	37.32	21.06	10.05
Sal mixed forest	48.15	31.15	14.65
Mean	46.43	30.06	12.97

The volume, biomass and carbon storage in different forest types are summarized in different slope categories of the study area in Table 7. Among the three slope classes, gentle slope class (0–20%) had the highest volume in all forests, followed by medium (21%–40%) and steep slope classes (>40%). In gentle slope class, the standing volume ranged from 51.23 to 93.02 m³·ha⁻¹, in moderate slope from 32.1 to 60.2 m³·ha⁻¹ and in steep slope class from 22.65 to 40.51 m³·ha⁻¹. The standing biomass varied from 74.65 to 103.23 Mg·ha⁻¹, 42.13 Mg·ha⁻¹ to 71.54 Mg·ha⁻¹ and 20.1 Mg·ha⁻¹ and 32.74 Mg·ha⁻¹ in gentle, medium and steep slope classes. The carbon storage for the above classes

The data revealed that trees present in gentle slope posses maximum volume, biomass and carbon. Results of this study also indicated that slope and aspect of sites had obvious effects on volume, biomass and carbon storage of dry tropical forests of Chhattisgarh, India. Integration of slope and aspect along with forest type was used to analyze the variation on vegetation, volume and biomass in a given forest type. Topographic factors modify the microclimate and edaphic conditions of a site, and responsible for determining the successional stage of vegetation

in a given habitat. Cook et al. (1989) demonstrated the importance of biogeographic data along with Landsat TM Remote sensing data in estimating the productivity and structure of North American forests. Ravan (1994) also integrated the slope, aspect and vegetation type information in GIS environment to estimate the structural and functional parameters of dry tropical ecosystems. The HVS (Homogenous vegetation stratification) method was found to be effective method for precisely estimating forest vegetation and biomass, compared to spectral models and also simple forest type stratification. Similarly, Swamy (1998) also reported that HVS was a better method, compared to spectral model for vegetation analysis and productivity of tropical evergreen forests of Karnataka, India.

The above ground biomass ranged from 45.94 to 78.31 Mg·ha^{-1} for different forests in the study area (Murphy et al. 1986; Singh et al. 1991; Roy et al. 1996; Haripriya 2000). Singh et al. (1979, 1991) reported that biomass was 42–78 Mg·ha^{-1} in dry tropical forests of U.P., India. Roy et al. (1996) by using HVS and spectral response model estimated the biomass of tropical dry deciduous forest of Madhav National Park, Madhya Pradesh, India. Hall et al. (1991) estimated the biomass of forests in South and South-East Asia using the volume estimates and biomass expansion factors derived from Brown et al. (1989). Tiwari (1994) reported that average value of above ground biomass density in different forest types of Rajaji national park, Dehradun, India ranged between 52.36 t·ha^{-1} (plantations) and 371.08 t·ha^{-1} (Sal forest). In present study the lower biomass estimates in dry tropical forests was due to the availability of immature trees and destruction of forest by the human interference. Moreover the management and gap filling in the forest was not done, which resulted to the poor biomass. However, the estimates in this study are more reliable as the expansion factors used were developed in Indian forests (Haripriya 2000). It is also evident from the results that classification accuracy for different forest types was not 100%, however it varied from 64% to 90%. The above reasons might have caused the under estimation of biomass in this study

The above ground carbon storage in the present study for different forest types ranged from 22.97 to 39.11 Mg·ha^{-1}C. The carbon storage of these forests are comparable to carbon storage in tropical forests in different localities (Schroeder 1992; Haripriya 2000; Shepherd et al. 2001). Haripriya (2000) reported that above ground biomass was from 97.3 to 48.3 Mg·ha^{-1}C (approximately 50% of the biomass) for tropical deciduous forests of India. Schroeder (1992) also reported that above ground biomass was from 8 to 78 Mg·ha^{-1}C available in fast growing plantations of *Acacia mearnsii*, *Casuarina equisetifolia*, *Cassia siamea* and *Azadirachta indica* in humid tropics. The carbon storage in the present study is much lower in range as compared to the estimates made in different tropical forests (Ajtay et al. 1979; Brown et al. 1982; Brown et al. 1994; Swamy 1998). Brown et al. (1982) estimated that the carbon storage was from 46 to 183 Mg·ha^{-1}C for variety of tropical dry forests of the world. Similarly, Swamy (1998) estimated that the carbon storage was from 94.3 to 190.96 Mg·ha^{-1}C in semi-evergreen forests of Karnataka, India. Brown et

al. (1994) observed that the carbon storage was from 95 to 157 Mg·ha^{-1}C for different tropical forests of Malaysia. The lower carbon storage in dry tropical forests of the present study might be due to availability of poor stand density and relatively less number of trees in present in higher diameter classes, compared to above forests.

It can be concluded that the forests of present study area are not fully mature as compared to the other tropical forests that resulted in higher carbon storage. Further, our study did not account for the below ground carbon, whereas the studies by other researchers considered below ground root carbon, which might cause the under estimation in the study. Brown et al. (1982) showed that below ground biomass varied between 10% and 40% (with an average of about 20%) of the above ground biomass in lowland tropical humid forests. Besides, the other possible causes for underestimation carbon storage were: Carbon content was not directly estimated in different plant components. The present study considered average 50% of dry biomass of tree as above ground Carbon content as that suggested by Brown et al. (1982); Dixon et al. (1994); Heath (2007); Haripriya (2000) and Houghton et al. (1993). However, C content varies from component to component and it is about 50 % for stem biomass and some time little lower for branch, root and dry foliage (Smith et al. 1997).

Results of this study also showed that among the different forest types, mixed forest type had highest above ground biomass (78.31 Mg·ha^{-1}) and carbon storage (39.11 MgC·ha^{-1}), compared to those in Teak and Sal mixed forests. The mixed forest had maximum NDVI value, which is quite evident in Fig. 6. The habitation, degraded forests and young Teak stands had lower NDVI values. The higher NDVI values represented the higher biomass and carbon storage levels in mixed forests, compared to those in other forest types. These results are supported by findings of several earlier workers (Spanner et al. 1990; Unni et al. 1992; Dutt et al. 1994; Swamy 1998). Spanner et al. (1990) and Running et al. (1986) reported that there were the good linear relationship and high correlation between NDVI and LAI in North western U.S. coniferous forests site. Further, the Leaf Area Index (LAI) had a strong functional relationship with stem wood biomass and NPP (Ghotz 1982; Waring et al. 1985). In all these studies, it was observed that the higher NDVI values represented the higher biomass in the forest and lower NDVI values.

The higher amount of biomass in mixed forest in comparison to other forest types in this study was also further supported by the findings of Shepherd et al. (2001), as they reported that amount of biomass was from 1.7 to 26.4 Mg·ha^{-1}C in 1-6 years old of pure/sole plantations of four species viz. *Albizia guachapepele*, *Dipteryx panamensis*, *Terminalia amzonia* and *Virola koschnyi*. The present study also showed that the higher number of species was found in mixed forest type, and they also yielded higher volumes and biomass subsequently revealed the maximum carbon storage. The presence of more number of trees in higher girth classes was responsible for maximum carbon storage in mixed forest, compared to other forest types in the present study.
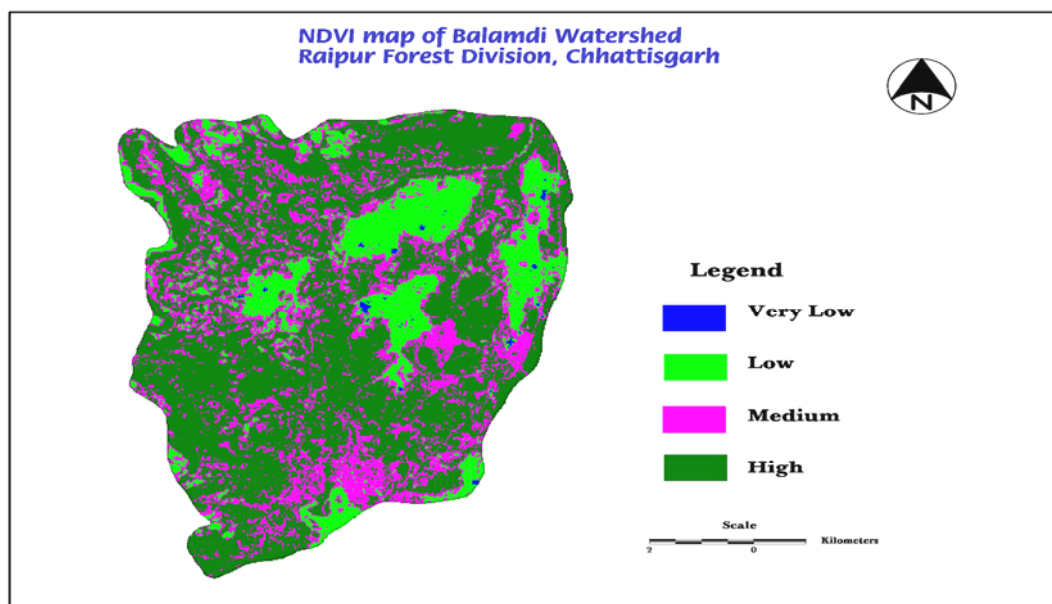
Fig. 6 Normalized Difference Vegetation Index (NDVI) map of Balamdi watershed

Standing volume, biomass and carbon storage in different forest types in the study area were also significantly influenced by aspect and slope of sites. The earlier studies also demonstrated that physiography had the marked influence on the growing stock, biomass and Carbon storage (Swamy 1998; Dhanai et al. 1999; Sharma et al. 2000). Sharma et al. (2000) studied that there was the variation in growing stock of high Himalayan and Siwalik Chir pine in different aspects of sites. The maximum growing stock (440 $m^3 \cdot ha^{-1}$) was found on the north-eastern aspect in high Himalayan Chir pine forests, whereas the lowest volume (67.76 $m^3 \cdot ha^{-1}$) was found in Siwalik Chir pine in the south-west aspect. Similarly, Swamy (1998) found that highest biomass (426.55 $Mg \cdot ha^{-1}$) and Carbon storage (190.96 $Mg \cdot ha^{-1}$) were in semi-evergreen forests in steep slopes of western aspect, whereas the lowest biomass (211.07 $Mg \cdot ha^{-1}$) and carbon (94.31 $Mg \cdot ha^{-1}$) were found in steep slope in the southern aspect. The present study showed that overall standing volume in dry tropical forests was the highest (52.00 $m^3 \cdot ha^{-1}$) in the northern aspect, while the maximum biomass (66.53 $Mg \cdot ha^{-1}$) and carbon storage (33.26 $Mg \cdot ha^{-1}$) were found in the southern aspect. The standing volume in northern aspect was higher by 2.5 $m^3 \cdot ha^{-1}$, while the biomass and carbon storage values were lower by 1.57 times in northern aspect, compared to those in the southern aspect. The forest containing higher volume generally had higher biomass and carbon storage. However, this study showed that the forest in the northern aspect had higher volume but comparatively lower biomass and carbon storage than forests in the southern aspect. The higher biomass and carbon storage in the northern aspect were due to the presence of more amount of Sal vegetation, which had greater wood density (0.75-1.1 $Mg \cdot m^{-3}$) and also higher expansion factor. In northern aspect, the concentration of mixed vegetation was higher, which had relatively lower wood density (< 0.75 $Mg\ m^{-3}$). The results also revealed that the standing volume, biomass and carbon storage were higher in the gentle slope class and lower in

steep slope class. The average standing volume ranged from 32.3 to 70.94 $m^3 \cdot ha^{-1}$, biomass from 25.95 to 92.87 $Mg \cdot ha^{-1}$ and carbon storage from 12.97 to 46.43 $Mg \cdot ha^{-1}$ in different slope classes (Table 7). The presence of higher soil depth and adequate water availability in gentle slopes resulted in higher growth in diameter and height of trees, which caused comparatively maximum volume, biomass and carbon storage. On the other hand, the steep slope are highly eroded and does not bear sufficient soil depth and moisture content, which resulted in poor growth and development of vegetation and subsequently caused lower biomass and carbon storage.

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